ACTIVITY REPORT

November 2002

Natural Gas & Oil Technology Partnership

bringing department of energy national laboratories capabilities to the petroleum industry

Los Alamos
Los Alamos, NM 87545
(505) 667-7811

Sandia
Albuquerque, NM 87185
(505) 844-7333

Lawrence Livermore
Livermore, CA 94551
(925) 422-5196

Lawrence Berkeley
Berkeley, CA 94720
(510) 486-5085

Argonne
Argonne, IL 60439
(202) 488-2415

Brookhaven
Upton, NY 11973
(516) 344-3819

Idaho
Idaho Falls, ID 83415
(208) 526-7004

Oak Ridge
Oak Ridge, TN 37831
(865) 574-4941

Pacific Northwest
Richland, WA 99352
(509) 372-4565

To: William F. Lawson, Director
National Energy Technology Laboratory
One West Third Street
Suite 1400
Tulsa, OK 74103-3519

From: J. Albright, Los Alamos
D.J. Borns, Sandia
J. Ziagos, Lawrence Livermore
N. Goldstein, Lawrence Berkeley
D. Schmalzer, Argonne
A. Goland, Brookhaven
B. Reynolds, Idaho
J. McFarlane, Oak Ridge
B. Saffell, Pacific Northwest

cy: E. Allison, DOE Fossil Energy
L. Capitanio, DOE Fossil Energy
G. Dehoratiis, DOE Fossil Energy
A. Hartstein, DOE Fossil Energy
B. Hochheiser, DOE Fossil Energy
E. Subia-Melchert, DOE Fossil Energy
N.B. Woodward, DOE Office of Science
D. Alleman, DOE-NETL-Tulsa
J. Casteel, DOE-NETL-Tulsa
N. Comstock, DOE-NETL-Tulsa
R. Lindsey, DOE-NETL-Tulsa
R. Long, DOE-NETL-Tulsa
K. Sterling, DOE-NETL-Tulsa
D. Sutterfield, DOE-NETL-Tulsa
J. Ammer, DOE-NETL-Morgantown
H. Guthrie, DOE-NETL-Morgantown
B. Gwilliam, DOE-NETL-Morgantown
J. Rogers, DOE-NETL-Morgantown
B. Tomer, DOE-NETL-Morgantown
F. Toro, DOE-NETL-Morgantown
M. Vargas, DOE-NETL-Morgantown

Note: Natural Gas and Oil Technology Partnership projects are reported according to the following schedule:

January, March, May, July, September, November	**February, April, June, August, October, December**
Drilling, Completion, and Stimulation Technology Oil and Gas Recovery Technology Diagnostic and Imaging Technology	Natural Gas Technology Upstream Environmental Technology Downstream Environmental Technology

Natural Gas and Oil Technology Partnership on the World Wide Web: http://www.sandia.gov/ngotp/

Drilling, Completion, and Stimulation Technology

Downhole Seismic Source for Look-Ahead Pore Pressure Prediction While Drilling

(Halliburton and INEEL)

The Regenerative Combustion Source (RCS) bench checkout was completed and downhole source testing started in November at the INEEL. Equipment problems during testing will require this experiment to be repeated.

The Capacitive Discharge Downhole Source (CDDS) prototype and a high-pressure vessel were used to evaluate the effects of at-depth pressures on the CDDS seismic signature. There was concern that the source output signature would diminish to zero as the at-depth pressure went past the supercritical point of water (3200 psi) at ambient temperature. Initial results indicate that there was no degradation of the seismic signature as the pressure went past the super critical point.

Acoustic Telemetry (MWD)

(ABB, Electroacoustics Research Laboratory, Extreme, and SNL)

Highlight:

- Documentation in preparation.

SNL is preparing the final documentation for this project.This includes a detailed description of the prototype tools, as well as a discussion of the field test results. SNL also continues to support the commercial development of acoustic telemetry with the project's industry participants through the development of a special reflector sub and the loan of one of the prototype tools for an in-house trade show.

Development of Chemically Bonded Ceramic Borehole Sealants

(GPRI, ANL, and LANL)

Highlight:

- Two sealant applications tested.

ANL continued testing the sealants for strength evolution after they are pumped. Since this methodical study is time consuming, ANL researchers decided to consolidate some feasible applications and demonstrate them for immediate use. ANL attempted two niche applications at the laboratory scale: 1) permafrost regions and 2) oil-based drill cuttings. Details are below.

Compatibility of the Sealants for Permafrost Environment

Setting of conventional cements in cold temperatures is difficult. Ceramicrete-based products that are used in road repair have shown excellent setting in very cold environments. Therefore, they can be very good candidates for permafrost applications that will include stabilizing the casing for first 600 feet (a regulatory requirement) and other surface and subsurface applications.

ANL tested the Ceramicrete-based sealant with Class C and F ashes using the regular consistometer to test pumping characteristics. A chiller was attached to the consistometer to maintain the slurry cup at 40°F. Pressure was maintained at 700 psi, which represents the pressure of a shallow well. The slurry was mixed as usual and poured in the slurry cup in the consistometer. Thickening was monitored as a function of time. The slurry thickness, measured in Bearden units, was low—in the range of 12–15 throughout the three-hour test. Afterwards, the slurry was cured in the slurry cup, and the temperature and pressure were maintained overnight. After 18 hours, the sealant had hardened into a single monolith showing that the sealant provides excellent low viscosity in a cold environment yet sets very well in cold temperatures.

Because the sealant can incorporate materials such as hollow silica spheres, ANL plans to reduce the thermal conductivity of the sealant to its lowest value possible and maintain the pumping characteristics unaltered.

Compatibility with Drilling Mud and Cuttings

To test if the sealant is compatible with drilling mud and cuttings, ChevronTexaco provided ANL oil-based cuttings for testing. The cuttings were very oily and in large chunks. ANL crushed and mixed them with the Ceramicrete sealant at different proportions. Loadings of the cuttings in the slurry varied from 20 to 70 wt.%. The mixed slurry was poured in ASTM standard cylinders of 2-in. diameter and 4-in. height. The slurry was allowed to set overnight at ambient temperature. The next day, samples with 20–60 wt.% had set into hard ceramics while samples with 70 wt.% loadings had not set. This implied that the sealant is very compatible with cuttings up to a loading of 60-wt.%.

Apart from the compatibility of the sealant with drill cuttings and mud for pumping purposes, the high loading demonstrated in this test opens up other applications for the sealant. Communications with ChevronTexaco experts indicated that conventional cement-based products do not stabilize cuttings well. For this reason, ChevronTexaco is interested in testing the Ceramicrete-based stabilized cuttings. The samples made in this project will be sent to ChevronTexaco for detailed testing. The tests will be conducted for physical properties of the stabilized products and their leaching characteristics. If successful, these sealants may also be used to stabilize the cuttings and clean up some of the oil field waste.

Coiled-Tubing Deployed Microdrilling with Real-Time, Downhole Monitoring

(DeepLook and LANL)

Highlight:

- Collaboration with SNL to deploy their two-part, polyurethane-foam lost-circulation material under consideration.

The microdrilling system was moved to the Fenton Hill site in late September for evaluating its performance in harder formations: the andesites and sandstones that lie below 350 ft (the bottom of volcanic tuff). A string of 2-3/8-in. OD steel pipe was run and cemented in an existing hole that was drilled to120-ft several years ago. The bore was deepened using a high-speed, 1:2 lobe, 1-7/16-in. OD, drilling mud motor and a 1-3/4-in. PDC drag bit. A new thermally stable diamond (TSD) bit was used to drill below 200 ft. A prolific lost circulation zone was encountered at 216 ft, which greatly impeded progress as the hole was drilled below that depth. Numerous attempts were made to seal off the permeable zones including treatments with bentonite chips, several bentonite grouts, gypsum cement, combinations of grouts and polymer, large volumes of mineral fiber/cellophane flakes in polymer, and polyacrylimide copolymers. The lost circulation zone has not yet been sealed. The hole was eventually drilled to 262 ft, with only occasional drilling-mud returns below 216 ft.

A collaborative effort with SNL is under consideration to deploy their two-part, polyurethane-foam, lost circulation material in the microhole. A successful field demonstration will allow LANL researchers to reach the target formations, and give SNL the opportunity for a small-scale field test.

Effects of Well Conditions on Post-Perforation Permeability

(Halliburton, Penn State, and LLNL)

Highlights:

- Completed a series of flow tests on cores of Berea sandstone and limestone.
- Analyzing X-ray CT images from two recent flow tests in Berea sandstone cores.

LLNL's enhanced computational model allows LLNL researchers to simulate the transient pressure surge following perforation. The pressure surge removes post-penetration debris and cleans up the damaged zone immediately adjacent to the perforation. LLNL coupled this model with the lab's previously developed fines migration model to investigate the relative influence of rock properties, fluid properties, and perforating conditions on post-perforation permeability. Recent efforts focused on the ongoing experimental efforts in support of model development.

Researchers completed a series of 15 API RP43 flow tests on cores of Berea sandstone and limestone over a broad range of underbalance pressures. Data

from these tests will be used to test the ability of LLNL simulators to predict measured core flow efficiencies. Project researchers are also analyzing X-ray CT images from two recent flow tests in Berea sandstone cores and are preparing two additional Berea sandstone samples for perforating and flow testing.

Lifetime Performance Monitoring of Synthetic Fiber Mooring Ropes

(Petroleum Composites, Puget Sound Rope, Shell, Whitehill Manufacturing, and ORNL)

Highlight:

- Tensile tests of rope specimens performed.

Tensile tests of rope specimens with integrated optical fibers were performed. The specimens were 5-mm diameter braided ropes constructed from eight multifilament strands. The rope specimens were load cycled in a tensile test machine to nominal strain values of 1%, 3%, 5%, and 7%. The tests showed good agreement between the applied strain and the measured strain in all cases. Typically, the measured strain closely follows the loading and unloading characteristics (hysteresis) of the rope specimen. Each specimen was load cycled at least 100 times, and in some cases was cycled more than 300 times. The optical fiber performed very well under this cycling, exhibiting good elastic recovery and with very little, if any, loss in transmission.

Variations of these tensile tests will continue in the next reporting period to investigate different load cycling scenarios and higher strain values, and to assess the efficacy of reflective interfaces.

Disposable Fiber Optic Telemetry System for Use With Coiled Tubing

(GTI, CTES, and SNL)

Highlights:

- Yard test of fiber conducted.
- Pump test conducted during integrity monitoring of fiber.

On September 24 an initial yard test consisting of injection and integrity verification of 1,100+ m was started. Initial results were marginal because of a number of factors that did not include the functionality of the injector. As the tests began, an injection rate of about 300 ft per minute was tried. The optical fiber broke almost immediately because the initial feed and the reel of optical fiber was unable to turn at this rate. The injection was restarted, and 150–155 m were injected at about 200 ft per minute. The fiber between the reel and the injector began to oscillate, and the fiber broke again The injection was restarted with the feed reel much closer (about 2 ft verses the initial try at about 7–8 ft) and the feed off of the bottom of the reel instead of the top. A slower feed rate was achieved, and the oscillations were minimized. However, the feed slowed down and stopped resulting in the fiber breaking again.

Disassembly of the injector revealed that the inlet tube and toe outlet tube of the injector were clogged with a fiber material. Investigation revealed that the filter in the water pump being used for fiber injection had deteriorated and the fiber substance in the injector was indeed filter particles. Using an optical time domain reflectometer (OTDR), it was determined that 745–748 m of fiber remained on the feed reel. A new filter was installed, and injection was restarted at a rate of about 60–70 ft per minute with the rate gradually increasing until control of the feed reel was lost and the fiber jumped off of the feed reel and wrapped around the shaft of the reel mount and broke. The next morning, the fiber that had been injected was measured with the OTDR revealing that 522–525 m had successfully been in injected.

On September 25, the remaining 200+ m of fiber was successfully injected at about 18 km/min. The length of the coiled tubing used for the final test was 5631 ft (about 1.85 km). The 2.4 km of optical fiber was loaded into the injector, and injection started at an average of 18 km/min. Control of the feed reel at this injection rate was exceptional. At 1 hr and 39 min, the 1.95 km of fiber was successfully injected. A pump test of about 4.5 hrs was continued

while the fiber was continually monitored for integrity. The fiber survived the limited pump test.

The fiber injection and the pump test were successful and future yard tests with a minimum of 16 hrs of pump tests on the injected fiber are planned, dependent upon funding. The yard test will be followed by a field test under actual downhole conditions, possibly during an acid injection, again dependent upon available funding.

Automatic Flaw Detection and Identification for Coiled Tubing (U of Tulsa, INEEL)

Highlights:

- Inspection apparatus and software assembled and tested.
- Inspection of first coiled tubing sample completed.
- Signal analysis initiated.

The research team attended the industry review of the Drilling Completion and Stimulation forum in Houston, TX. At the forum, the team presented a poster entitled "Automatic Flaw Detection and Identification for Coiled Tubing."

Work has begun to create a library of signals from defects of various sizes and types. The signals are being analyzed to look for characteristic signal features that can be used to classify defects. Plots of various defects were made using Matlab analysis package to determine the feasibility of using 3D plots for signal discrimination.

Laboratory inspection equipment was completed and tested with good results. The inspection of the first coiled tubing sample was accomplished and development of signal analysis initiated. Activities in this phase included:

- Motion of a linear slide was tested and tuned to determine the maximum rate of acceleration and if a velocity of 3 ft/s could be reached in a 6-in. distance. Results indicate that the slide can meet this requirement.
- Hall probes were mounted in inspection shoes to provide a mechanism to maintain constant standoff distance between the hall probes and the surface of the coiled tubing that is being inspected. The standoff is important when quantifying or relating eddy current signal strength to defect size, position, and depth.
- Inspection shoes were mounted inside of a magnetic coil using a fabricated spring clip. The clips provide a constant force to hold the hall probe inspection shoe assembly against the surface of the coiled tubing.
- An energy chain was mounted to the experimental apparatus. The energy chain provides strain relief for the wires connecting the coil and the data acquisition isolation box while the coil is in motion during inspection of the coil tube.
- Initial software to control linear slide and data acquisition during inspection was developed. The software also displays data for the experimental investigator's evaluation during development.

Laboratory Study on Borehole Stability and Sand Production in Weakly Cemented Sand (ChevronTexaco, Shell, and LBNL)

Highlight:

- Sonic frequency acoustic device built and tested.

A sonic frequency acoustic device for measuring the viscoelastic moduli of weakly cemented sand was built, and preliminary tests were conducted on synthetic materials (aluminum and Plexiglas) with well-known properties. Test results showed large attenuation (damping) of the acoustic energy by the device itself. To reduce this attenuation, LBNL researchers made a few modifications to the experimental setup. The viscoelastic moduli of the materials are determined from measured vibration frequencies using the device using a 1D numerical code.

LBNL researchers are conducting preliminary tests (optical microscopy study) on five kinds of silica sand, each with a different grain geometry. Samples of weakly cemented sand will be made using these sands and tested for their mechanical and acoustic properties. The angularity of sand grains is an important parameter for borehole sand production and breakout, since angu-

larity can be related to the intergranular friction and lock-up, which increases the rock's frictional strength and resistance against hydrodynamic erosion.

In the second year of the project, LBNL will conduct laboratory borehole breakout and sanding experiments under anisotropic stress and with fluid flow within and around a borehole drilled in weakly cemented sand samples. In order to start the experiment at the beginning of the second year, a "true" triaxial test cell, capable of applying the three principal stresses to the sample independently, has been designed in the past month. The test cell has an aluminum wall so that X-ray CT scans can be performed during the experiment. The construction of the cell will start early in 2003.

Development of Smart-Proppant Technology for Hydraulic Fracturing

(U of Tulsa, and INEEL)

Highlight:

- Poster presented at the International Petroleum Environmental Conference.

Work continues on the development of polymeric carrier systems for inclusion of industrial specified materials and systems. Contemporary results support the use of nomex coated systems for application as a competent model system. Efforts include applying nomex coating technology to a variety of materials appropriate for use. Ammonium persulfate/guar gum systems are being used for evaluation. Important development criteria include release profiles, efficacy parameters, delivery concerns, and application envelope.

Greg Bala, of INEEL, J. Liang, of INEEL, and Kerry Sublette, of the University of Tulsa, prepared and presented a poster, "Development of 'Smart' (Reactive) Proppant Technology for Hydraulic Fracturing," at the NGOTP meeting held in Houston.

Publications

Mathew, T., W. Redman, K.L. Sublette, and G.A. Bala. "Development of Smart Proppant Technology for Hydraulic Fracturing: Polymeric Carrier System for Active Agents," poster presented at the Ninth Annual International Petroleum Environmental Conference, Albuquerque, NM, October 22–25, 2002.

Application of High-Powered Lasers to Drilling and Completing Deep Wells

(GTI, PDVSA, Parker Geosciences, Colorado School of Mines, and ANL)

Highlights:

- Week-long series of tests conducted at ANL to simulate *in situ* well drilling downhole environments.
- Initial trials to drill deep, narrow holes useful for perforation.
- Paper accepted for publication.

In a week-long series of tests to simulate *in situ* well drilling downhole environments, which involves liquids such as drilling mud, water, and oil, the team carried out laser testing of rock samples in liquid to 1) understand laser power attenuation through water and 2) determine the most efficient laser parameters to lase rock through water. The tests were performed using both of ANL's high-power lasers, the 6 kW carbon dioxide (CO_2) laser and 2.0 kW Nd:YAG laser on rocks having two different water-related configurations: free water above submerged rock samples and a cross-flowing water jet over top of the rock surface. The results provide the basis for, and drive home the importance of, developing equipment to properly: 1) inject the beam into a water environment without the interface problems inherent in a free water-air surface and 2) provide a purge with a high-nozzle velocity to remove melted material as well as divert the plume of debris. Holes were drilled into limestone for comparison tests between continuous wave (CW) and superpulse (SPP) beams from the CO_2 laser. Three gas-purging configurations were tested. A smaller specific energy (SE) was achieved by SPP beam. However, as the hole became deeper, the difference of SE for the two operating modes became smaller and smaller, and finally disappeared. This was caused by secondary effects.

The paper, "Specific Energy for Pulsed Laser Rock Drilling" has been accepted for publication in the February 2003 issue of the *Journal of Laser Applications*.

Oil and Gas Recovery Technology

Improved Waterflooding Through Control of Brine Composition and Other Factors (BP Amoco, U of Wyoming, and INEEL)

Work continues on the final report. INEEL researchers are waiting for final revisions from the University of Wyoming.

Measuring Sucker Rod Pump Parameters Downhole (Harbison-Fischer, UT-Austin, and SNL)

Highlight:

- Equipment to upgrade instrumented pump at UT-Austin acquired.

A new hollow polished rod for the instrumented pump at the University of Texas has been manufactured. This will allow a cable to be threaded through the polished rod to a specially fabricated load cell. With a load cell below and above the stuffing box, stuffing box friction can be measured directly. Tests of pump performance with high-viscosity oil were completed. Tests using a pressure gauge mounted above the traveling valve, but ported to the compressing chamber, were also completed. The new pressure transducer provides a direct measurement of pump fillage. Previously, determinations of pump fillage have relied on interoperation of dynamics.

Formation Logging Tools for Microboreholes (DeepLook and LANL)

No work scheduled for this reporting period.

Coupled Geomechanical Deformation, Fluid Flow, and Seismic Modeling (Mobil, Schlumberger, UT-Austin, and SNL)

Highlight:

- JAS3D modified to compute an element based rock compressibility value.

Modifications were made to JAS3D to compute an element based rock compressibility value. This rock compressibility value is computed for each element in the geomechanics model using rock constitutive model parameters. The element based rock compressibility value will then be passed to IPARS where it will be used as part of an algorithm to adaptively control the frequency of data transfer between the flow simulator, IPARS, and the geomechanics code, JAS3D.

Mechanisms of Oil Recovery and Validation of Corefloods (ChevronTexaco, ConocoPhillips, and LBNL)

Highlight:

- Important and unique code developed that can be used to predict the pore connectivity of sedimentary rocks from the distribution of grain sizes and the depositional environment.

Conversion of rock images from micro CT-tomography and depositional models into pore networks is necessary for obtaining the representative capillary pressures and relative permeabilities. This conversion is especially important for unconsolidated or weakly consolidated rocks, which disintegrate upon coring. From the distribution of grain sizes and the depositional environment, a synthetic rock sample can be generated and converted into an equivalent pore network. LBNL researchers have developed a unique algorithm that provides not only the true pore connectivity, but also the associated volumes and shapes. To our knowledge, only the LBNL code has such robust characteristics. The other codes, most notably 3DMA, frequently fail and give coordination numbers (pore connectivity) as high as fifty for uniform sphere packings that are not aligned with the image axes.

A visualization tool with a user-friendly graphical interface has also been developed. The tool allows the user to inspect the output of the pore-network extraction code at the level of an individual pore body (node) or pore throat (link). The entire pore space can also be visualized. The tool has been imple-

mented on a PC. It is based on the 3D graphics library, OpenGL and, therefore, can be ported to any platform supporting OpenGL. Using this tool, LBNL made important corrections to the pore network extraction code.

Direct Simulation of Near-Wellbore Mechanics

(ChevronTexaco, Halliburton, Schlumberger, Shell, MIT, NM Tech, and SNL)

Highlights:

- Researchers have begun to develop simulations of cavity formations in unconsolidated sands.

Work continues on the refinement and application of the 2D code, and the development of a non-spherical discrete element for the 3D code. In addition to the principle investigator, project staff contributing during this period include graduate interns Dave Boutt, of NM Tech (NMT), and Scott Johnson, of Massachusetts Institute of Technology (MIT). We have begun to develop simulations of cavity formations in unconsolidated sands. During the testing of small-scale models, we realized that the realism of our simulations was limited by elementary boundary conditions and forcing schemes. To address this deficiency, we implemented a new boundary condition that allows for specified fluid pressures at in-flow and out-flow boundaries. In 3D, we are continuing our research into alternate, more realistic particle representations to the commonly used spherical discrete-element. We have implemented a recently published pseudo-ellipsoidal representation, which shows great promise as a computationally compact and physically realistic representation for natural particles like sands. We are in the process of refining the previously proposed contact detection algorithm for this representation, with preliminary numerical results suggesting a potential for a several-fold speedup in computational efficiency.

Finally, our collaboration with NMT and MIT continues to mature with our joint submission (along with the University of Oklahoma and several industry participants) of a $1 million proposal to NPTO to apply the models being developed under this program to simulate proppant transport. We are awaiting the formalization of the licensing agreement by the SNL legal department, which will allow NMT to begin beta testing our codes.

Publications

Cook, B.K., D.R. Noble, and J.R. Williams. "A Coupled DEM-LB Model for the Simulation of Particle-Fluid Systems," accepted for publication in the *Proceedings of the 3rd International Conference on Discrete Elements Methods*, Ed. Cook and Jensen. ASCE.

Cook, B.K., M.Y. Lee, A.A. DiGiovanni, D. R. Bronowski, E.D. Perkins, and J.R. Williams. "Discrete Element Modeling Applied to Laboratory Simulation of Near-Wellbore Mechanics," accepted for publication in the *International Journal of Geomechanics*.

Lee, M.Y., B. K. Cook, A.A. DiGiovanni, E.D. Perkins, and J.R. Williams. "Simulation of Borehole Failure Phenomena Using Discrete Element Modeling," *Eos Transactions*, AGU, 82(47), T51A-0846, 2001.

Well Integrity Assurance for Sub-Salt and Near-Salt Deepwater GoM Reservoirs

(BHP, BP Amoco, ChevronTexaco, ConocoPhillips, ExxonMobil, Halliburton, Kerr-McGee, Shell, and SNL)

Highlights:

- 3D non-linear finite element analyses reveal perturbations surrounding salt bodies.
- 2D non-linear finite element analyses reveal critical role of hole quality.

A series of 3D non-linear finite element analyses to determine the perturbation in *in situ* stresses adjacent to salt bodies was completed. A total of 18 finite element meshes were developed to consider four idealized geometries: a spherical salt body; a horizontal salt sheet; a salt diaper, and a salt diaper with tongue. Analyses were performed for two non-lithostatic values of the far field stresses. The analyses reveal stress perturbations surrounding salt bodies that have profound implications for wellbore stability prediction during drilling. The analyses reveal: 1) shear stress may be highly amplified at certain locations around

salt bodies; 2) horizontal and vertical stresses can be significantly perturbed from their far-field values in certain regions surrounding salt bodies; 3) principal stresses are not necessarily vertically and horizontally aligned in some regions proximal to salt bodies (i.e., the vertical stress may not be equal to the maximum stress); and 4) anisotropy in the two horizontal stresses may be induced for some regions adjacent to salt bodies, depending on specific geometry.

A suite of wellbore-scale 2D non-linear finite element analyses was completed to assess salt loading on through-salt well casings over the well service lifetime. The analyses include initial transient creep behavior following excavation (drilling), and subsequent closure behavior over a 30-year service lifetime. More than 100 non-linear finite element analyses were conducted for four typical deepwater GoM casing/hole configurations, including two different borehole qualities. The analyses reveal the critical role of hole quality, and can be used to quantitatively estimate the necessity, or lack thereof, for cementing the annulus between the casing and borehole. The focus of this effort is to enable a screening program whereby operators may assess the approximate loading on through-salt well casings.

A project meeting was held at Shell BTC's offices in Houston on October 29. Thirteen representatives of the participating companies attended the meeting. Recent technical work was presented, and goals and directions for Year 3 were discussed. Following the meeting, individual company meetings were held at Kerr-McGee, ExxonMobil, and BHP in mid-November. Additional meetings at ChevronTexaco, ConocoPhillips, and Shell's SEPCo office in New Orleans are planned for early 2003.

The third year proposal was presented to a DOE/industry review panel in Houston on November 13. Each of the participating companies plans to enter into another 2-year funding agreement with SNL for Years 3 and 4 of the project. However due to the merger of Conoco and Phillips, there will be only eight partners for Years 3 and 4.

An Integrated Approach to Assessing Seismic Stimulation

(Aera Energy, ASR, BP Amoco, ChevronTexaco, ConocoPhillips, Halliburton, Marathon, OGCI, Piezo Sona-Tool, Schlumberger, Shell, UC-Berkeley, LBNL, and LANL)

Highlights:

- Improvements made to allow better characterization of dynamic-stress induced changes in fluid flow behavior.
- New rock samples obtained.
- Sensitivity analysis performed for the numerical modeling of the boundary value problem.

Field Experiments

Project researchers are designing the next test, which will record in two wells simultaneously at different distances. The sensors will be the same 3-C clamping tool used in the initial tests, and the other sensor will be a newly acquired two-level (2-m spacing) hydrophone. Stepping away from the source in the same horizon will enable measuring the attenuation and signal strength in the reservoir horizon, thus providing input to the numerical modeling effort. Instrumentation was sent to OGCI in October to monitor a test of their source in test block.

Laboratory Work

Previous laboratory experiments at LANL demonstrated that dynamic stress cycling of sandstone cores during 2-phase fluid flow causes significant changes in the fluid distribution in the rock. Several physical mechanisms have been proposed to explain these observations, including altered wettability, *in situ* fines migration, and fluid boundary film disruption. In addition, physical parameters from several previous experiments are being used as inputs to the University of California-Berkeley numerical modeling efforts, and comparisons between numerical predictions and experimental results are being made. Start-up efforts at LANL under the new project have focused on modifications to the laboratory equipment, refinements to the experimental procedures, and improvements to the fluid delivery and stress/strain measurement systems.

These improvements will allow better characterization of dynamic-stress induced changes in fluid flow behavior. Several new rock samples were obtained and are being prepared for testing. These include field samples from producing reservoirs where stimulation tests are planned or ongoing. Finally, a new design was devised for constructing a direct pore-pressure stimulation source. This will be used to investigate the effectiveness of this mode of stimulation relative to the mechanical-stress mode used in previous experiments.

Theoretical and Modeling

The constitutive equations describing two-phase flow in a deformable porous medium were finalized and work started to implement them into a numerical modeling code. Sensitivity analysis was performed for the numerical modeling of the boundary value problem involving the decoupled Biot equations subject to a periodic fluid pressure pulse imposed on a constant pressure gradient. Results show that the optimal stimulation frequency required to induce maximum fluid flow depends on permeability, the inertial coupling parameter, Young's modulus, Poisson's ratio, porosity, and cylinder length of the core sample. We have been able to generalize the linear stress-strain relations for a single-fluid system to a two-fluid system. Results show that the linearized increment of fluid content for a two-fluid system can be derived in the context of mass balance. It involves three key components: frame contraction and the differences in intrinsic volumetric strain between the solid and each of the two fluids. A paper is in press on the initial derivation of the mass and momentum equation governing pressure stimulation.

High-Resolution Microseismic Monitoring of Reservoir Processes (ABB Offshore Systems, ChevronTexaco, Shell, and LANL)

Highlights:

- Tested event classification and waveform correlation techniques on Cotton Valley microseismic datasets.
- Presented Cotton Valley re-analysis results at the SEG Annual Meeting.

LANL started tests of automating the high-precision picking on the Cotton Valley data. The high-amplitude horizontally polarized shear phases (SH) generally have good signal-to-noise ratios. We were successful in grouping these events into preliminary groups and obtaining correlated picks comparable in precision to the manually identified re-picks. Waveform stacks based on the automated and manual repick alignments showed comparable amplitudes. The classification was also successful separating the events groups based on SH polarities, important in identifying source mechanism groups. Results of these tests were presented at the Society of Exploration Geophysicists Annual Meeting.

The proposal for this project was presented as a new proposal requesting continuation and full funding. Of the new proposals presented, it ranked #2.

Direct Quantification of Uncertainties Associated with Reservoir Performance (ChevronTexaco and LANL)

LANL researchers continue developing computational algorithms to parallelize and modify the existing code for single-phase fluid flow in heterogeneous reservoirs. Testing and debugging the code is ongoing.

The proposed moment-equation (ME) approach has to be validated before it can be applied to the real world, and the Monte Carlo (MC) simulation has been used to complete that validation. The MC simulation entails generating a large number of equally likely random realizations of the reservoir fields with parameter statistics. Parameter statistics are then derived from sampling, and are the same as assumed in the ME approach, solving deterministic flow equations for each realization, and post-processing the results over all realizations to obtain sample moments of the solution.

LANL then compared the mean and variance derived from the ME approach against those from the MC approach. It is evident that, for the reservoirs with variance of log permeability up to 1.0, results from the ME approach agree with those from MC approach very well. However, the ME approach is computationally less demanding than the MC approach.

Diagnostic and Imaging Technology

Advanced Sensor Technology for Microborehole and Other Seismic Instrumentation

(Input/Output and LANL)

The project consultant from Houston traveled to Los Alamos, NM, to review the project and take part in the next experimental phase. The data taken to date were reviewed and it was discovered that some of the data were contaminated with digital "glitches" from the recording system. The glitches have been removed, and analysis continues to determine if the removal was effective or if the data needs to be retaken. It was also decided that a hydrophone needs to be added to sensors being tested to complete the experiment. An appropriate hydrophone was identified, obtained and is being laboratory tested. Field tests should resume shortly.

Inversion of Full Waveform Seismic Data for 3D Elastic Parameters

(Amerada Hess, ChevronTexaco, ConocoPhillips, Fairfield Industries, GX Technology, Marathon, Unocal, and SNL)

The project is in close-out phase. A final report will be issued.

Next-Generation Seismic Modeling and Imaging

(Advanced Data Solutions, Anadarko, BHP, BP Amoco, ChevronTexaco, ConocoPhillips, Core Laboratories/Tomoseis, ExxonMobil, Fairfield Industries, Fugro Geoservices, GeoCenter, Geophysical Development, GX Technology, Marathon, Mitchell Energy, Paradigm Geophysical, PGS, Shell, Unocal, Veritas DGC, WesternGeco, Society of Exploration Geophysicists [SEG], Stanford, U of Houston, LANL, and LLNL)

Highlights:

- Calculation of synthetic elastic data in SEG/EAEG Salt structure continues.

The calculation of synthetic elastic model data in the SEG/EAEG salt structure continues. An additional 50 shots were calculated, which brings the total number of shots calculated to about 150. The full survey that has been defined comprises 289 shots. Two types of receivers are being used: simulated marine streamers and simulated ocean bottom cables. Several vertical seismic profiling (VSP) instruments will be added for remaining shot calculations.

This is the last year for the current project. A proposal for a new modeling and imaging project was prepared and presented to the Diagnostic and Imaging review panel in November in Houston. That proposal was one of six new project proposals presented. Final results of the panel review are expected by January or February 2003.

Rapid Imaging of Interwell Fluid Saturations Using Seismic and Multiphase Production Data

(BP Amoco, ChevronTexaco, ConocoPhillips, Exxon-Mobil, JNOC, Landmark, RC2, Statoil, Tomoseis, Total-Fina-Elf, Texas A&M, and LBNL)

LBNL researchers have completed a comparison of numerical and streamline-based permeability sensitivities. These quantities form the basis for the LBNL iterative inversion algorithm. Earlier in the summer LBNL compared porosity sensitivities computed using numerical and streamline-based approaches. Computing the numerical permeability sensitivities required modifying the code to run in double precision. The comparisons indicate the accuracy of the streamline-based method which is three-orders of magnitude faster than the numerical technique. LBNL has set up a synthetic test case, which is similar in many respects to the project's actual Gulf of Mexico field situation.

LBNL researchers formulated an approach to account for transverse processes in the lab's streamline simulation code. Furthermore, LBNL has examined the scaling with problem size of two approaches for solving the inverse problem. The first is the conventional iterative inversion method based upon a regularized least-squares methodology. The second is a Baysian methodology for inverting water-cut observations. The study highlights the advantages of the iterative least-squares approach both in memory requirements and computational efficiency.

Offshore Oil Field Characterization with EM Methods

(Scripps, Texas A&M, and SNL)

Highlight:

- Efforts focused on development of the finite element forward modeling program.

Efforts in the last two months have focused on development of a finite element (FE) forward modeling program to compute the magnetotelluric (MT) response of electrically resistive geologic features such as the Gemini salt structure in the Gulf of Mexico (GoM). The key issue addressed by the modeling is to assess the ability of the magnetotelluric method in characterizing the base of salt—an area difficult to image with seismic methods but of great commercial interest because of its spatial relationship to hydrocarbon reserves. Testing of the FE code has shown favorable agreement between FE solutions and those derived from analytic formulae for simple problems. Preliminary results on the sensitivity of the MT response to deep rooted salt structures (based on the Gemini prospect, GoM) indicate that the base of salt manifests itself in the period range of 200–20 s as a ~10% anomaly in the apparent resistivity estimate. This is near the noise threshold of marine MT data and emphasizes the continued need for close collaboration between instrumentation development, data analysis, and numerical modeling efforts. These results will be presented in a special session on electromagnetic methods at the upcoming 2002 Fall Meeting of the American Geophysical Union.

Innovative Wave-Equation Migration

(Advanced Data Solutions, Amerada-Hess, Applied Geophysics Services, Baker Atlas, BHP, ConocoPhillips, Exxon-Mobil, Fairfield Industries, GX Technology, Petroleum GeoServices, Screen Imaging, Shell, TomoSeis, Unocal, Veritas DGC, and LANL)

Highlight:

- Talks given at SEG meeting.

LANL researchers gave two talks at the Society of Exploration Geophysicists meeting: one on the split-step Fourier Pade migration method, and another on limited-aperture migration. Research continues on wave-equation migration in the offset domain.

Project researchers have started investigation of the stationary-phase common-azimuth wave-equation migration. The main purpose of both research topics is to provide more efficient wave-equation migration schemes. With the help of Dr. Zhiming Li from Unocal, LANL has started pre-processing a real

3D dataset provided by Unocal. LANL researchers are modifying the 3D wave-equation migration codes to deal with irregular receiver distribution of the real 3D dataset.

Testing and Validation of High-Resolution Fluid Imaging in Real Time (DeepLook, KMS Technologies, KJT Enterprises, U of Wisconsin, LBNL and SNL)

Highlight:

- On the basis of the work done by LBNL, SNL, and the University of Wisconsin, Shell is prepared to invest significant funds to pursue the next stage of fabricating the prototype borehole seismic, EM single-well system.

Borehole Seismic, Seismic and EM System Integration, Field Testing

Work focused in two areas: 1) fabrication, testing, and modification of the LBNL single-well system integration, and 2) testing the EM sources with the LBNL system for noise analysis. The single-well system was upgraded with new electronics from OYO to combine fiber-optic telemetry into a more efficient and compact design, and to provide real-time remote access to the data acquisition for real-time processing and interpretation. An improved single-well source was fabricated and tested, which is smaller, higher frequency, yet just as powerful. A new tube-wave suppressor for smaller wells was fabricated and tested. In the testing and integration of EM components, an EM receiver and electronics was built by KMS Technologies, and fully integrated and tested with the LBNL single-well fiber-optic system. Noise surveys were acquired with the 24-bit system for determining overall system sensitivity, bandwidth, and noise floors. This information played an important role in Shell's overall decision to proceed to the prototype phase of the work.

3D EM Model Validation, Sensitivity, Directionality

SNL focused on the development of a perturbation expansion solution to the governing Maxwell equations with the goal of addressing two particular model geometries (a isotropic quarterspace and an isolated, compact anomalous block, each within a homogeneous background). The modeling efforts reached the stage where comparisons with independent solutions are feasible, providing the foundation for comparison of the perturbation expansion solutions with independently derived solutions. With funding from KMS Technologies/Shell, the University of Wisconsin (UW) initiated an electromagnetic modeling study using SNL-developed code. The purpose of the study is to determine the sensitivity of the proposed EM portion of the new tool to 3D inhomogeneities, to analyze the response of different source-receiver combinations, and determine how the trajectory of the borehole relative to the target affects the "data." With funding from LBNL, the modeling study will continue with a short-term goal to finish all of the different source-receiver configurations and positions of interest to the industry consortium, and to duplicate the effort for a second model. Time permitting, a study will be undertaken to determine the effects of a metal mandrel on the response of the proposed EM logging tool.

3D Seismic Model Validation, Sensitivity, and Directionality

SNL conducted numerous computational simulations of reflection and diffraction responses observed by a single-well seismic data acquisition tool. The simulation of the tool consists of a point energy source and four, near-offset, multi-component particle velocity receivers. The earth models investigated include an isolated low-impedance geologic bed and a quarter-space with a strongly diffracting corner. Medium properties represent typical Gulf Coast sedimentary materials. Synthetic seismograms are calculated with an explicit, time-domain, finite-difference algorithm appropriate for isotropic elastic media. Calculated traces exhibit dramatic variability in character, depending on orientation and proximity of the recording tool with respect to the reflecting/diffracting horizons. Interference of reflection arrivals with the direct wave also presents a challenge.

Autonomous Monitoring of Production

(Aera Energy, ChevronTexaco, SteamTech Environmental Services, TomoSeis, and LLNL)

The time-lapse casing survey obtained over the 11-well pattern obtained in September was processed, and the results are being analyzed in conjunction with production records from the field. The time-lapse data correlate with production history. Field measurements remain consistent, with acceptable data quality obtained during normal field operations. The primary change of the 4-month period is a decrease in electrical in the portion of the field of a few percent. This decrease is most pronounced in the vicinity of the well in which a pronounced increase in oil/water ratio had been obtained in response to water injection in the area. The overall area of decreased resistivity is coincident with the region of greatest fluid injection and movement. These results can be interpreted in terms of water displacing oil in the pore spaces, which is consistent with both the injection and production results. The second-most pronounced change in the field resistivity occurs in the vicinity of the well that experienced the second-highest increase in oil/water ratio over the same time period. A subsequent time-lapse casing survey is scheduled for early December.

Optimizing access for use in remote fields requires a robust communication system. In other applications, electrical resistivity tomography (ERT) surveys are being remotely conducted on a daily basis utilizing phone lines for direct links to the acquisition system. A wireless transmission system will permit unmanned access on a routine basis. System optimization for remote field use requires enhancements in both communications and in power transmission for data acquisition. LLNL researchers are addressing both issues through development of a more stable power supply that has standard power requirements rather than the special generator used for high-resolution point electrode measurements and by identifying satellite systems capable of delivering robust communications at sufficient rate for field use. The power supply was obtained; it will be field tested during the casing survey scheduled for December. A satellite communications system has been identified and configuration and testing is scheduled for January, 2003.

Anisotropic Properties of Compacted Clay-Rich Rocks

(BP Amoco, ChevronTexaco, ConocoPhillips, LBNL)

Efforts focused on: 1) fabrication of the clay compaction cell at LBNL, and fabrication of the P-wave and S-wave ultrasonic transducers at ValpeyFisher Corp., Hopkinton, MA, 2) plane-wave synthesis tests with an ultrasonic P-wave phased array and a 1-mm-diameter piezoelectric P-wave transducer (called a "pinducer"), and 3) development of an inversion algorithm for determining the elastic constant c13 from plane P-wave measurements made over a range of angles of incidence (relative to the axis of symmetry of the compacted clay).

Fabrication of the clay compaction cell is about 95% complete. The last detail remaining is the machining of the holes in the loading piston to accommodate the pore pressure line and the P-wave pinducer. This should be completed in December 2002.

The practical details of using a phased array source and a pinducer receiver to measure plane P-waves over a range of angles of incidence were examined using a 32-element, P-wave phased array and a broadband pinducer. Tests on a 6.35-mm-thick aluminum disk demonstrated that it is possible to reliably phase and record P-waves over a range of angles of incidence in an isotropic material. Tests are now being conducted on a standard orthotropic material, phenolite, with three planes of symmetry.

LBNL will now fabricate the 1 MHz P-wave phased array and install it into

the compaction cell. This will complete the cell construction and allow researchers to commence anisotropy measurements on clean clays and on the industry provided cores.

Realistic Anisotropic Velocity Estimation in Complex 3D Environments (BP Amoco, ChevronTexaco, ConocoPhillips, Kerr-McGee, Shell, TomoSeis, LBNL)

Analysis of techniques for estimating velocity anisotropy from seismic data continued. In particular, LBNL researchers implemented "selective-correlation velocity analysis" (Celis et al., 2002) for vertically-transverse isotropic (VTI) media. By using a selected subset of all possible cross-correlations, rather than all possible ones in a common midpoint gather (CMP) or a common image gather (CIG), we can improve both the reliability and resolution of NMO velocity and effective anisotropy parameter, h. The basic idea of this method is to include only the cross-correlations for those pairs of traces whose relative differential move-out of reflections exceeds a chosen threshold value. This technique can be used for VTI velocity analysis on CMP or CIG gathers. LBNL implemented a VTI velocity analysis code using the selective-correlation method and is testing its applicability on numerical data generated from realistic structural models.

Because the selective-correlation method is not normalized, the weaker reflections are hard to see within the dynamic range of display (equal amplitude range for both panels). Analysis is now concentrating on the application of this method to noisy data.

Work continued on LBNL's modified titled TI finite difference code. In many cases the symmetry axis of anisotropy is not perpendicular to structural interfaces. In order to model these cases, the existing FD TTI (tilted transverse isotropy) code had to be made more flexible. The code was modified so that the axis of symmetry can vary from cell to cell. In the constitutive relations, all stress components depend on all strain components for titled TI models.This means that the staggered grid scheme becomes awkward and cannot be solved without the use of additional operations to interpolate wavefield components and elastic moduli between staggered grid nodes. This has been implemented in the new version and comparisons made to our pseudo spectral code to validate travel times. Testing and validation of the new code continues.

Joint Geophysical Imaging (ExxonMobil, UT-Austin, SNL, and LBNL)

Highlight:

- Testing and evaluation of the EM and seismic inverse algorithms continued.

EM Inversion

Previously, SNL preformed a 1D EM sensitivity study where a 30 m-thick layer that was 50% oil saturated was varied in depth between 500 m–2500 m, and determined that there was sufficient EM response to make this a viable target. In November SNL constructed a realistic 3D model of a petroleum reservoir and generated a number of numerical simulations of the EM response for different source-receiver configurations. Based on this 3D model SNL researchers concluded that 1D models are sufficient for determining the optimum system configurations for targets at different depths.

The numerical data from the 3D simulations were used to construct several inverse runs where the new 3D inversion algorithm is used to estimate the electrical conductivity structure from the observed data. In initial tests it was observed that the direct fields emanating from the transmitter swamped the fields coming from the reservoir for receivers too near to the source. This means that there is an optimum source-receiver separation where the signal from the target (reservoir) divided by the primary (or direct) fields from the transmitter is a maximum. This also means that to get aerial coverage over the reservoir, a number of transmitter locations is required with the optimal source-receiver

separation. The CPU run time of the inversion codes is linearly proportional to the number of transmitters, so researchers made a trade off between maximum spatial resolution of the reservoir and CPU time. A number of 3D inversions were initiated to delineate the minimum number of transmitters needed in what configuration to resolve the reservoir conductivity structure in an optimal fashion. This inversion testing continues.

Seismic AVO Inversion

SNL continues to develop the AVO inversion algorithm for estimating acoustic (Vp) and shear (Vs) velocity and density from the amplitudes of seismic reflections as a function of source-receiver offset. Initial testing considered simple 1D models and field data from Chevron. In order to verify the algorithm, SNL constructed a 2D numerical model based on US Gulf of Mexico geology and generated synthetic numerical data. This numerical data is being processed though the standard industry processing flow to generate a more complex synthetic data set for algorithm testing.

SNL's current AVO algorithm works in the time-domain and estimates Vp, Vs, and density at interfaces in time. This assumes that the reflector events in time can be placed in depth based on other information (most commonly well logs). The inversion is also a linear operation on Vp, Vs, and density at a single reflection point. SNL began coding a new non-linear inversion that is parameterized in depth and operates on multiple reflection points simultaneously. The approach has the advantage that it allows incorporating spatial smoothing constraints to stabilize the solution. This means that the code solves for Vp, Vs and density at a user specified number (usually 5–7) of reflection points simultaneously subject to the condition that the Vp, Vs, and density varies as little as possible over the chosen number of reflection points. This is geologically reasonable and reduces the inherent non-uniqueness of the inverse problem.

Partnership Office

Industry Reviews Completed

The Partnership completed the fiscal year 2003 reviews of new proposals and ongoing projects in Houston, during November. Industry panels reviewed projects in the Drilling Completion and Stimulation, Oil and Gas Recovery, Diagnostics and Imaging, and Upstream Environmental technology areas. There was a significant turnout this year by the industry reviewers. Industry also had substantive discussions with DOE regarding ways to improve the Partnership. Once again, we thank the individual industry reviewers for their time and effort.

We have completed the tabulation of the industry ranking in the four technology areas. We will wait until the federal budget for fossil energy R&D is finalized later in the fiscal year before making the final project selections and funding levels.

Review Schedule Adjusted

In the coming years, the Partnership proposal and review schedule will be 6–8 weeks later in the fiscal year than in the past four years. By moving the schedule, the reviews will mesh better with the DOE program schedule. Approximately, the shift will result in the call for preproposals to be issued in early September, the proposals to be due in early October, and the selection of preproposals in mid-November, and the technology area reviews in January.